A Planetary Evolution Model for simulating Mars' past environments: preliminary applications to the Polar Layered Deposits

J.-B. Clément, **F. Forget**, **E. Vos**, **L. Lange** and **E. Millour**, *Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, Sorbonne Université, CNRS, Paris, France (jean-baptiste.clement@lmd.ipsl.fr)*.

Introduction: Mars experienced dramatic environmental changes over geological time, driven in large part by variations in its obliquity, between 0° and 60° [1]. These shifts strongly impacted atmospheric pressure, ice stability and the distribution of surface and subsurface reservoirs, leaving lasting geological features. Reconstructing this long-term climate evolution is essential to understand the planet's past environments and present-day ice reservoirs such as the North Polar Layered Deposits (NPLD) [2].

However, simulating these processes over millions of years remains challenging. Existing models struggle to bridge the gap between detailed short-term climate simulations and planet-scale, long-term evolution. To address this challenge, we developed the Planetary Evolution Model (PEM), a new numerical framework designed to simulate Mars' climate evolution over orbital timescales.

The Planetary Evolution Model: The PEM overcomes limitations of traditional General Circulation Models (GCM), which accurately resolve climate physics but are computationally restricted to short periods, and simpler 1D models, which oversimplify key dynamical couplings and rely on prescribed reservoirs or fluxes, limiting their realism.

The PEM employs an asynchronous coupling strategy with a GCM, here, the Mars Planetary Climate Model (PCM) [3], to focus on long-term evolution of reservoirs while bypassing sub-year variability. It derives tendencies from yearly-averaged data of two consecutive PCM years and extrapolates them over extended periods of time until predefined stopping criteria are met (*e.g.* surface pressure change, ice area loss/gain or orbital shift). The updated climate state then feeds new PCM simulations to refresh tendencies, repeating this cycle to cover orbital timescales. Key physical processes included in the PEM are:

• *CO_2/H_2O surface ice evolution*. Local tendencies are computed from interannual minima of the ice in the PCM (perennial ice). The PEM assumes fast atmospheric equilibration for water with only transfers between sublimating and condensing reservoirs.

• *Glacier flow*. A statistical sub-grid slope parameterization accounts for North–South orientation effects [4], reproducing slope-dependent layering.

• *Subsurface H_2O ice*. Ice table depth is dynamically adjusted based on thermal diffusion, pressure and surface humidity, following Norbert Schorghofer's work [5].

• *Soil properties*. The PEM uses a multilayer subsurface (regolith, breccia, bedrock) whose thermal properties adapt to pressure and pore-filling ice. The yearly-averaged surface and subsurface temperatures are updated according to surface ice accumulation/depletion.

• *CO_2/H_2O adsorption/desorption*. Adsorbed species are maintained in equilibrium with the atmosphere.

Furthermore, the PEM performs several subsequent adaptations to make the aforementioned processes internally consistent and to simulate the co-evolution of reservoirs and atmosphere. For instance, the PEM adjusts the yearly-averaged surface pressure based on CO_2 mass balance. This necessitates scaling the volume mixing ratios accordingly and to correct the CO_2 ice tendency obtained from the PCM.

These features allow the PEM to be used for two main goals: (i) to determine the steady-state configuration (*e.g.* realistic distribution of glaciers) for given orbital parameters, which can then be used as initial states in other simulations; and (ii) to track the fate of reservoirs due to Mars' climate changes under orbital forcing scenarios.

Preliminary applications to the Polar Layered Deposits: As a first application, we used the PEM to simulate the formation and evolution of the Martian NPLD. They exhibit a complex stratigraphic structure made of layers with varying composition (H_2O ice, dust and possibly temporary CO_2 ice) and geometry (thickness, unconformities). They preserve stratigraphic records of past climate conditions during their formation [6,7]. Their alternating dusty and icy layers are thought to reflect obliquity-driven cycles of ice accumulation and depletion, provided that a source is available [8,9].

The PEM includes a layer-tracking approach that updates the local stratification by adding, removing or modifying layers in response to deposition and sublimation events. It accounts for dust lag layer formation which happens upon ice sublimation and may prevent ice from further loss if it is buried enough. The possibility to create water ice lag above CO_2 glaciers, as observed and modeled by Buhler *et al.* [10] for the South Polar Layered Deposits (SPLD), is also taken into account. Preliminary simulations aim to test whether the PEM can reproduce observed patterns of the NPLD stratigraphy and to evaluate the role of orbital forcing in shaping the deposits. They offer a first case study demonstrating the model's potential decode Mars' climate history.

Perspectives: The PEM is designed as a flexible tool to investigate Mars' long-term climate evolution. While early applications focus on Polar Layered Deposits, its scope goes well beyond. Ongoing work includes improved subsurface ice dynamics, simulations of atmospheric collapse and inflation scenarios, and coupling with planet-scale hydrological model (lakes and river systems) for early Mars. By enabling consistent, physically based simulations of Mars' climate over geological timescales, the PEM offers a powerful new approach to explore "Mars through time" and to interpret the planet's rich geomorphological record.

Bibliography:

[1] Laskar J. et al. (2004) Icarus, 170(2), 343–364.

[2] Smith I. B. et al. (2020) Planetary and Space Science, 184, 104841.

[3] Forget F. et al. (1999) J. Geophys. Res., 104(E10), 24155–24175.

[4] Lange L. et al. (2023) Journal of Geophysical Research: Planets, 128, e2023JE007915.

[5] Schorghofer N. (2007) Nature, 449, 192-194.

[6] Phillips R. J. et al. (2011) Science, 332, 838.

[7] Levrard B. et al. (2007) J. Geophys. Res., 112, E06012.

[8] Hvidberg C. S. et al. (2012) Icarus, 221(1), 405-419.

[9] Vos E. et al. (2022) J. Geophys. Res., 127(3), e2021JE007115.

[10] Buhler P. B. et al. (2020) Nature Astronomy, 4, 364-371.